

PLANT CANOPY EFFECTS ON WIND EROSION SALTATION

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ABSTRACT. Maintaining standing vegetative soil cover is an important method of wind erosion control. However, an improved physical understanding of the mechanisms by which standing vegetation control wind erosion is needed so the erosion control level of vegetation not previously tested in a wind tunnel can be calculated. In this report, a theoretical approach that accounts for both the surface friction velocity reduction and the saltation interception by standing stalks is proposed. The predictive ability of the theory is then tested using two previously published data sets from wind tunnel studies in which soil loss was measured. The results show a high correlation between plant area index of stalks and soil protection. However, some initial tunnel experimental data on simulated plants with two movable leaves indicate that both plant area index and aerodynamic roughness may be needed to fully assess the erosion control level of canopies with leaves. **Keywords.** Soil erosion, Standing residue.

Establishing and maintaining a vegetative soil cover comprise an important method of wind erosion control (Woodruff et al., 1977). In order to develop conservation plans that provide adequate protection against wind erosion, the level of soil protection provided by a wide range of flat and standing vegetative cover must be assessed. Because of the importance of vegetative cover, a number of wind tunnel studies have measured soil loss and/or threshold wind speeds on both real and simulated vegetation (Armbrust and Lyles, 1985; Hagen and Lyles, 1988; Lyles and Allison, 1976, 1980, 1981; van de Ven et al., 1989).

However, to develop a widely applicable, physically based simulation model such as the Wind Erosion Prediction System (WEPS) (Hagen, 1991a), additional information on sparse vegetative canopies is needed. First, a theoretical framework is needed that can be used to interpret the meaning of wind tunnel tests of standing vegetation, when the results are to be applied on a field scale. Second, a large number of single as well as combinations of plant species for which conservation planners must provide control estimates have not been tested in wind tunnels. Hence, the minimum set of plant parameters necessary to model the protective level of standing vegetation must be identified.

In this report, a theoretical approach to describe the effects of uniform standing vegetation on wind erosion saltation on a field scale is presented. To test major

assumptions, the theory is then applied to previously published experimental data on standing stalks and to some new data on a simulated canopy with leaves. Based on the analysis, minimum sets of plant parameters needed to model the protection level of uniform standing vegetation are suggested.

THEORY

A sparse, uniform canopy is illustrated in figure 1. A so-called, log-law layer exists above the canopy in which the wind speed profile follows a semilogarithmic profile and the friction velocity remains constant throughout the height of the layer (Panofsky and Dutton, 1984). Because wind erosion occurs only at relatively high wind speeds, we will assume that the boundary layer stability is near neutral during erosion events. Hence, the wind speed profile in the log-law region above the canopy has the well-known form:

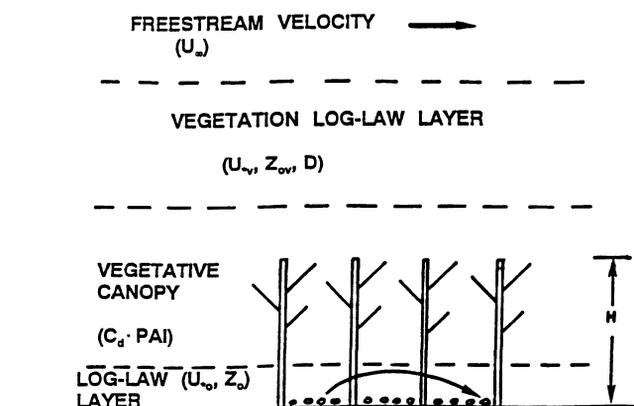


Figure 1—Schematic of stalk canopy illustrating above- and below-canopy friction velocity.

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$$U = \left(\frac{U_{*v}}{0.4} \right) \ln \left[\frac{(Z - D_v)}{Z_{ov}} \right] \quad (1)$$

where

- U = wind speed (L/T)
- U_{*v} = friction velocity (L/T)
- Z = height above the soil surface (L)
- D_v = aerodynamic displacement height (L)
- Z_{ov} = aerodynamic roughness length (L)

Below the log-law layer, the friction velocity, U_{*v} , is reduced in proportion to the stem and leaf areas in the canopy multiplied by their respective drag coefficients to the value of the friction velocity, U_{*o} , at the soil surface. The latter value is then available to drive the erosion process. A log-law wind speed profile also may occur close to the soil surface, but this feature has not been conclusively demonstrated.

On agricultural soils, the erosion process can be modeled as the time-dependent conservation of mass of two species (saltation and creep-size aggregates) with two sources of erodible material (emission and abrasion) and two sinks (surface trapping and suspension) (Hagen, 1991b). In typical, experimental studies of standing vegetation, the erosion system is generally simplified in order to illustrate only the main effects of the standing vegetation. For such a system in which the flow is one-dimensional and steady-state and the surface is covered with loose-erodible sand, the conservation equations reduce to the form:

$$\frac{dq}{dx} = c_{env}(q_c - q) - Tq \quad (2)$$

where

- q = saltation discharge (M/LT)
- x = distance from nonerodible boundary along wind direction (L)
- q_c = saltation discharge transport capacity without stalk interception (M/LT)
- c_{env} = emission coefficient, vegetated surface (3)
- T = interception coefficient (1/L)

The basal area of the stems in the typical sparse canopies of interest generally occupy less than 1% of the surface area. Hence, the surface emission coefficient is close to that of the same surface without standing vegetation.

In order to determine T, assumptions about the spatial distribution of the saltating particle cloud and the interception efficiency of individual stalks are necessary. In sparse stalk canopies with wind directions which cross the rows, the stalk-spacing-to-stalk-diameter ratio generally exceeds 30. Hence, both replacement of intercepted particles by surface emission and horizontal diffusion can act to reduce horizontal particle concentration gradients in stalk wakes. Thus, horizontal concentration of particles across the wind direction approaching individual downstream stalks was assumed to be uniform.

Individual stalks remove the particles from the air stream by inertial impaction and perhaps other mechanisms. Because the saltating particles have high inertia, stalk interception efficiency should be near 100%

(Hinds, 1982). Maximum saltation height was assumed to be less than stalk height.

With the preceding assumptions, the interception coefficient for a canopy of uniform stalks can be derived as:

$$T = C_t \left[\frac{PAI}{H} \right] \quad (3)$$

where

- H = vegetation height (L)
- PAI = plant area index, i.e., in this case stalk silhouette area per unit ground area
- C_t = interception coefficient of individual stalks, value about 1

Finally, integration of equation 2 over the field length, l, using the initial condition $q(x=0) = 0$ gives:

$$q = q_c \frac{c_{env}}{c_{env} + T} \left\{ 1 - \exp \left[- (c_{env} + T) l \right] \right\} \quad (4)$$

Note that the first set of terms on the right side of equation 4 defines the transport capacity of the surface with standing vegetation, whereas the second set of terms governs the rate of saltation increase toward transport capacity. Because stalks do not affect q_c , it can be estimated from a typical transport capacity formula (Greeley and Iverson, 1985):

$$q_c = C_s U_{*o}^2 (U_{*o} - U_{*t}) \quad (5)$$

where

- C_s = saltation discharge coefficient ($M T^2/L^4$)
- U_{*t} = soil surface dynamic threshold friction velocity (L/T)

For uniform loose soil U_{*t} can be calculated from particle diameter. To complete the equations needed for analysis, two empirical equations were developed from data sets in the literature. To determine the driving friction velocity at the soil surface, U_{*o} , one must first determine the aerodynamic roughness length, Z_{ov} , and compute U_{*v} . Empirical equations were fitted to parameter data reported by Hagen and Lyles (1988) to give:

$$\frac{Z_{ov}}{H} = \frac{1}{A + \frac{B \ln(C_d PAI)}{(C_d PAI)} + \frac{C}{(C_d PAI)}} \quad (6)$$

where

- A = $28.41 - 3.72 \ln(d_v)$
- B = $-3.052 + 0.6 \ln(d_v)$
- C = $-8.33 + 1.541 \ln(d_v)$
- d_v = diameter of stalks (mm)
- C_d = drag coefficient, measured values about 1 for long stalks

An example of the results is shown in figure 2.

When the above-canopy friction velocities were not reported in a data set, the freestream wind speeds and the

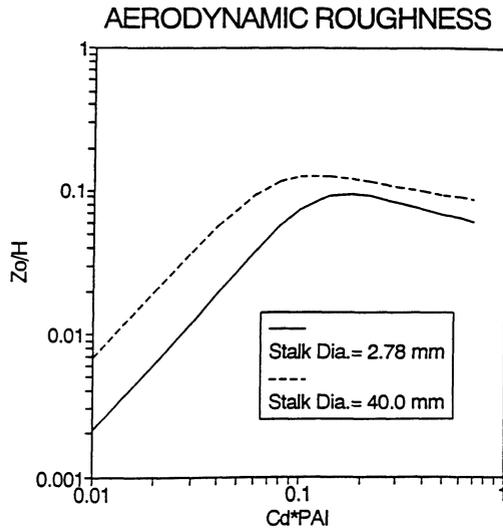


Figure 2—Examples of dimensionless aerodynamic roughness predictions using equation 6.

relationship shown in figure 3 were used to estimate the friction velocities. These data were collected in prior wind tunnel studies in the same tunnel used to obtain several of the data sets analyzed in this study. An equation fitted to the data gives:

$$\frac{U_{*v}}{U_{fs}} = -0.0153 - 0.0001407 [\ln(Z_{ov})]^2 - \frac{0.467}{\ln(Z_{ov})}$$

$$Z_{ov} > 0.0005 \text{ m} \quad (7)$$

where

U_{fs} = freestream wind tunnel velocity (L/T)

Next, the ratio of U_{*o}/U_{*v} must be determined. A sensitive indicator of U_{*o} can be obtained from experiments that report static threshold wind speeds. The ratios of below-canopy to above-canopy friction velocities

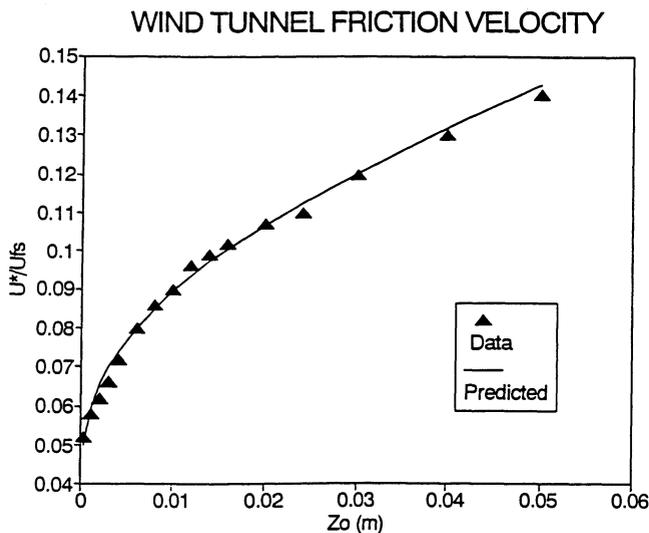


Figure 3—Ratio of friction velocity to freestream wind velocity as a function of aerodynamic roughness.

were calculated for the data set of Lyles and Allison (1976) using $U_{*o} = 0.291 \text{ m/s}$ and unpublished values of free stream static threshold velocities. Data reported by van de Ven et al. (1989) using $U_{*o} = 0.43 \text{ m/s}$ also were analyzed (fig. 4). Both data sets are for simulated plant stalks in wind tunnels. An exponential equation was then fitted to the data to give:

$$\frac{U_{*o}}{U_*} = 0.86 \exp\left(\frac{-C_d PAI}{0.0298}\right) + 0.25 \exp\left(\frac{-C_d PAI}{0.356}\right)$$

$$R^2 = 0.89 \quad (8)$$

EXPERIMENTAL DESIGN

Two sets of wind tunnel data with soil loss from trays were selected from the literature for testing the theoretical prediction equations. For the first data set, dowels were used to simulate plant stalks (van de Ven et al., 1989). For the second, more extensive data set, stalks were used from seven crops: cotton, forage sorghum, rape, silage corn, soybeans, sunflowers, and winter wheat (Lyles and Allison, 1981). Plant area indices were calculated for all of the stalk test data.

In addition, some preliminary wind tunnel data on simulated standing vegetation with two leaves, resembling soybeans, were collected. A laboratory wind tunnel, 1.52 m wide, 1.93 m tall, and 16.46 m long, with a recirculating push-type design and a 10-blade, axivane fan was used for the test. Simulated plants were mounted on the downwind 15-m section of the tunnel floor, which was then covered with 0.29- to 0.42-mm sand. A fence of triangular-shaped spires was installed at the upwind end of the tunnel to enhance initial generation of a thick boundary layer. The simulated plants extended 8 cm above the sand surface. Average characteristics of the individual plants were 48.8 cm² of leaf area, 2.43-cm²-stem area, and 0.26-cm-basal stalk diameter. The plants were mounted in rows normal to the wind stream and arranged in a diamond

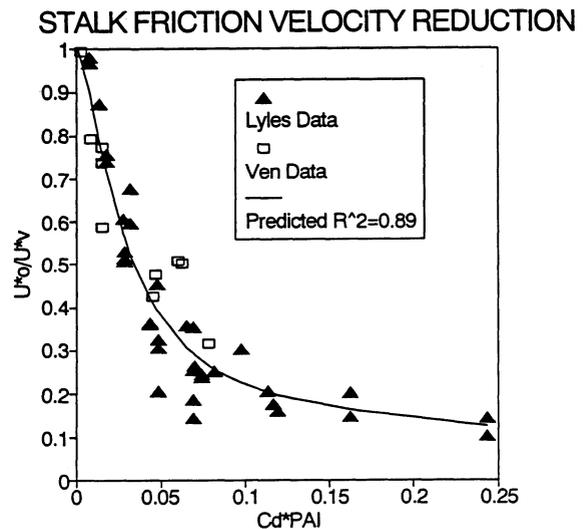


Figure 4—Calculated ratio of below-canopy to above-canopy friction velocities for data of Lyles and Allison (1976) and van de Ven et al. (1989).

pattern with 20.3-cm in-row spacing and a 40.6-cm between-row spacing. Multiple wind speed profiles were measured near the downwind end of the tunnel over the entire boundary layer. Methods outlined by Molion and Moore (1983) were used to calculate aerodynamic displacement height, and the method suggested by Ling (1976) for analyzing multiple profiles was used to calculate aerodynamic roughness. In addition, horizontal drag of individual plants was measured with a load cell.

Two configurations of the leaves were tested under a range of wind speeds. First, two leaves were mounted near the top of the main stem. Next, the leaves were mounted near the bottom of the main stem, close to the sand surface.

RESULTS AND DISCUSSION

Predictions of soil loss from the tray were calculated for the two sets of stalk data using the theory outlined in equations 4 through 8 (fig. 5). A critical assumption in the theory is embodied in equation 8, which suggests that all height, diameter, and spacing arrangements of stalks that result in a given PAI will produce the same ratio of U_{*o}/U_{*v} . In general this assumption cannot be true. Nevertheless, over the typical ranges of stalk parameters simulated in the test data sets, predicted saltation values accounted for 0.82 of the variance in the observed values.

Hence, as a first approximation one can use PAI alone as an indicator of wind erosion protection by standing stalks. In field use of the current wind erosion equation, residue weight is input; however, it is directly correlated to PAI. In the upcoming revised wind erosion equation, PAI will likely be used explicitly.

The data in figure 5 tend to show a bias toward over-prediction of the saltation. Investigation of the bias indicated that soil-surface friction velocity tended to be overpredicted in canopies as aerodynamic roughness increased. Thus, in order to improve saltation predictions in standing stalks, U_{*o}/U_{*v} probably should be computed as a function of both PAI and Z_{ov} . For the stalk data sets in this study, adding Z_{ov} to the prediction equation increased R^2 from 0.89 to 0.91.

The transport capacity of the stalk-covered surface, q_{cv} , from equation 4 is:

$$q_{cv} = q_c \left[\frac{c_{env}}{c_{env} + T} \right] \quad (9)$$

Equation 9 illustrates the fact that among the stalks, even in a simplified experimental system, the transport capacity depends on three factors: the soil surface friction velocity to drive q_c , the net rate at which saltation particles are emitted to the airstream, and the stalk area available for interception. Note that a surface that has a reduced emission coefficient and thus, is unable to quickly resupply intercepted particles will have a lower transport capacity than a surface with a high emission coefficient.

Three downwind saltation discharge values were calculated using equation 4 and are illustrated in figure 6. For a bare surface and for two surfaces with stalks — one with wind direction perpendicular to the row with $T = 0.1$, and one with wind parallel to the row with $T = 0.0$. Note that even a sparse standing-stalk canopy is highly effective in reducing transport capacity. The role of interception is also important. In this example, with wind parallel the rows, the lack of stalk interception permits the transport capacity of the surface to increase about 26%.

Finally, equation 4 predicts that the downwind distance to reach transport capacity on the stalk-covered surface will be less than that of a similar surface not covered with stalks. This occurs because the stalks occupy a small surface area and, thus, have little effect on emission coefficient. As a result, the rates of downwind increase in the saltation discharge will be nearly equal on a bare or stalk-covered surface, but the transport capacity is lower so is reached at less distance on a stalk-covered surface than on a bare surface.

When leaves are present in a standing vegetative canopy, the situation becomes more complex. It is difficult to predict the degree to which the leaves streamline parallel to the wind direction. Fortunately, the position of the

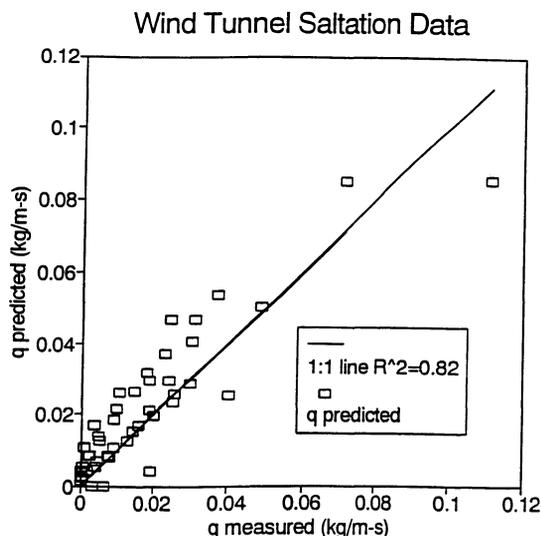


Figure 5—Predicted and measured saltation discharge for data of Lyles and Allison (1981) and van de Ven et al. (1989).

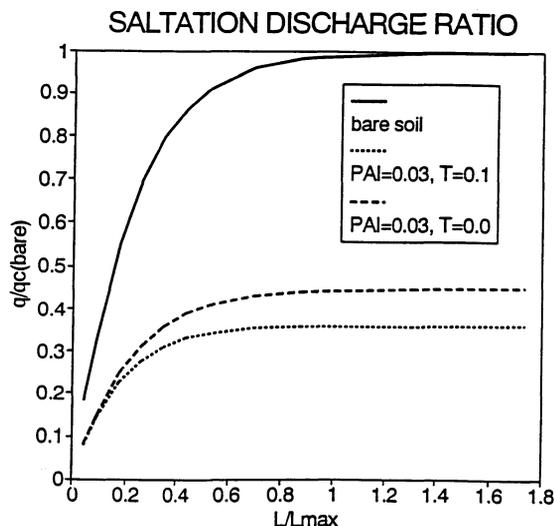


Figure 6—Illustration of effects of stalk interception on transport capacity.

maximum leaf area relative to canopy height remains the same throughout most of the growing season in the major agronomic crops (Armbrust, 1993; Bilbro, 1991). However, the bulk of the leaf area may be positioned near the top, middle, or bottom of the canopy, depending upon the vegetation type.

The effect of leaf position in the canopy was tested using artificial plants with two leaves. The drag on an individual plant was largest when the leaves were near the top of the canopy and increased with the square of wind speed (fig. 7). The aerodynamic roughness also decreased with the leaves near the bottom of the canopy (table 1). Finally, the ratio of below-canopy to above-canopy friction velocity varied significantly, even though the total stem and leaf areas remained constant. Thus, in canopies with leaves, the ratio of below-canopy to above-canopy friction velocity is likely to be a function of leaf area, stem area, and aerodynamic roughness of the canopy. Further investigation is needed to clearly define these relationships in sparse canopies with leaves.

CONCLUSIONS

In sparse, uniform stalk canopies, there is a high correlation between the plant area index and the soil protection level. Hence, the use of this single parameter to represent stalk canopies in erosion models appears justified for typical standing crop stubble densities. Theoretical analysis of the stalk canopy shows the transport capacity in such canopies is controlled by at least three factors—the plant frontal area per unit volume available for particle interception, the emission coefficient of the soil surface, and the friction velocity at the soil surface.

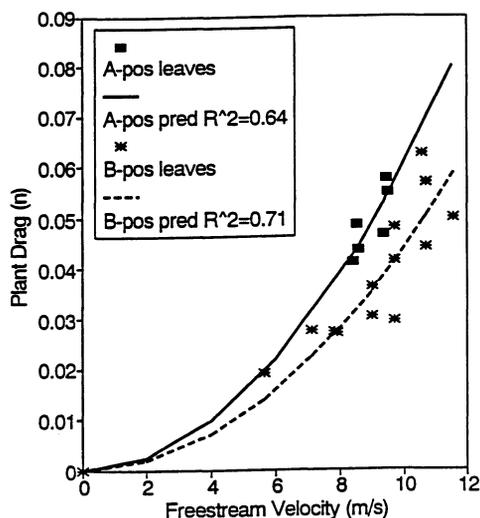


Figure 7—Plant drag of simulated plants with two leaves near top (A) or bottom (B) of canopy.

Table 1. Measured aerodynamic parameters of 0.08-m-tall artificial canopy with two leaves

Leaf Position	Aerodynamic Roughness (m)	Aerodynamic Displacement Length (m)	Threshold Friction Velocity (m/s)	Below/Above Canopy Friction Velocity Ratio
Top - A	0.0078	0.038	0.84	0.30
Bottom - B	0.0026	0.020	0.69	0.37

Initial experimental data on simulated plants with two movable leaves indicates that both plant area index and distribution of the leaves within the canopy are needed to accurately assess the level of soil protection by these canopies.

REFERENCES

- Armbrust, D. V. 1993. Predicting canopy structure of winter wheat and oat for wind erosion modeling. *J. of Soil and Water Conservation*. (Submitted).
- Armbrust, D. V. and L. Lyles. 1985. Equivalent wind erosion protection from selected growing crops. *Agronomy J.* 77(5):703-707.
- Bilbro, J. D. 1991. Relationship of cotton dry matter production and plant structural characteristics for wind erosion modeling. *J. of Soil and Water Conserv.* 46(5):381-384.
- Greeley, R. and J. D. Iverson. 1985. *Wind as a Geological Process*. Cambridge, England: Cambridge Univ. Press.
- Hagen, L. J. 1991a. A wind erosion prediction system to meet user needs. *J. of Soil and Water Conserv.* 46(2):106-111.
- . 1991b. Wind erosion mechanics: Abrasion of aggregated soil. *Transactions of the ASAE* 34(3):831-837.
- Hagen, L. J. and L. Lyles. 1988. Estimating small grain equivalents of shrub-dominated rangelands for wind erosion control. *Transactions of the ASAE* 31(3):769-775.
- Hinds, W. C. 1982. *Aerosol Technology*. New York: Wiley & Sons.
- Ling, C. H. 1976. On the calculation of surface shear stress using the profile method. *J. Geophys. Res.* 15:2581-2582.
- Lyles, L. and B. E. Allison. 1981. Equivalent wind-erosion protection from selected crop residues. *Transactions of the ASAE* 24(2):405-408.
- . 1980. Range grasses and their small-grain equivalents for wind erosion control. *J. Range Manage.* 33(2):143-146.
- . 1976. Wind erosion: The protective role of simulated standing stubble. *Transactions of the ASAE* 19(1):61-64.
- Molion, L. C. B. and C. J. Moore. 1983. Estimating the zero-plane displacement for tall vegetation using a mass conservation method. *Boundary-Layer Meteorol.* 26:115-125.
- Panofsky, H. A. and J. A. Dutton. 1984. *Atmospheric turbulence*. New York: John Wiley & Sons.
- van de Ven, T. A. M., D. W. Fryrear and W. P. Spaan. 1989. Vegetation characteristics and soil loss by wind. *J. of Soil and Water Conserv.* 44(4):347-349.
- Woodruff, N. P., L. Lyles, F. H. Siddoway and D. W. Fryrear. 1977. How to control wind erosion. USDA-ARS, Agric. Inf. Bull. 354 Washington, D.C.: GPO.